# Breakdown of Gate Oxides During Irradiation with Heavy Ions[†]

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*Abstract*

Breakdown of gate oxides from heavy ions is investigated. Soft breakdown was observed for 45 Å oxides, but not for 75 Å oxides. Lower critical fields were observed when experiments were done with high fluences during each successive step. This implies that oxide defects play an important role in breakdown from heavy ions and that breakdown occurs more readily when an ion strike occurs close to a defect site. Critical fields for 75 Å oxides are low enough to allow gate rupture to occur at normal supply voltages for ions with high LET.

## I. INTRODUCTION

Although gate rupture of power MOSFETs from heavy ions has been studied for many years, such effects have only recently been observed in high-density digital circuits. Permanent damage attributed to catastrophic gate breakdown from heavy ions was first reported in 1994 for 4-Mb DRAMs [1]. Later work showed that similar effects occur in the oxide-nitride sandwich structure used in programmable gate arrays [2]. It is important to note that breakdown from heavy ions occurred in both types of structures when they were biased at normal operating voltages. Although the threshold LET for breakdown to occur was well beyond the "iron threshold" in the galactic cosmic ray spectrum, data on DRAMs showed that the threshold for damage was lower for scaled devices, with higher electric fields across the insulator structure. The issue of how scaling affects catastrophic damage to the gate regions of VLSI devices, and how the mechanisms for damage relate to processing controls and oxide defects, is a complex issue which is still being investigated.

Last year, Sexton, et al. reported the results of a study of breakdown in capacitor structures, along with a more limited evaluation of breakdown effects in static memories [3]. Most of the devices that they studied had thinner gate oxides than the devices in the initial studies in References 1 and 2, and Sexton, et al. concluded that the gate rupture problem would be less severe for highly scaled devices with thin gates.

The present paper extends the earlier work on breakdown effects, including new factors such as the presence of soft breakdown characteristics in oxides below 60 Å, and the dependence of the critical field on fluence. Experimental results on capacitors from a different fabrication process were observed to have lower critical breakdown fields than reported in Reference 3. Breakdown in the new capacitor structures devices occurred with applied voltages that were within the range of electric fields expected for scaled devices. Possible reasons for the differences in experimental results are discussed, along with evidence for the likely role of oxide defects in the gate-rupture process.

## II. BASIC CONSIDERATIONS

### A. *Capacitors vs. Integrated Circuit Structures*

There are important differences between capacitor test structures and integrated circuits that must be taken into account when evaluating gate rupture effects. Although capacitors provide certain advantages, several complications arise when one attempts to extend capacitor results to circuits. The main advantage of capacitor test structures is that they provide explicit control of the electric field across the oxide, over a wide range. For most circuits, the field can only be changed over a limited range, imposed by circuit power supply voltage limitations. However, VLSI circuits can be viewed as a very large number of "test structures" within a single package, with the inherent ability to measure many different breakdown events, and statistical distributions of gate-rupture failures on a single device[1,2]. For capacitors, in most cases, only a single breakdown can be identified on an individual capacitor. This severely limits the ability to determine the statistical variability of gate rupture effects on capacitors unless extremely large numbers of capacitors are available.

The area of capacitor structures also plays an important role. In most cases the area of individual

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capacitors is many times larger than that of individual MOS transistors, but significantly lower than the total gate area of all MOS devices on a large-scale device. Other differences between capacitors and VLSI devices are shown in Table 1.

Table 1. Features of Capacitors and VLSI Devices of Importance in Oxide Rupture Studies

| | Oxide Field | Number of Events | Perimeter to Area Ratio | Lateral Field |
|---|---|---|---|---|
| VLSI Devices | Limited by circuit operating voltage range | Many on a single device | Small | Present |
| Capacitors | Can be directly controlled | Usually one | Very large | None |

The doping level of the silicon underneath the oxide may also be important because it affects the magnitude and time response of transient currents and voltages within the underlying silicon region. The capacitors that were tested in Reference 3 and those tested in the present work were all fabricated over very lightly doped silicon regions (~ $10^{15}$ $cm^{-3}$). Doping levels in MOS devices beneath the gate region are one-to-two orders of magnitude higher, and it is possible that capacitor results on more lightly doped material may be different from the gate rupture tolerance of the same oxides over material with higher doping levels.

Another potentially important difference between capacitors and gate regions is the perimeter area ratio which is three-to-four orders of magnitude higher for individual gates than for capacitors. Edge effects – which may be influenced by the nonplanar nature of silicon and oxides near the periphery – are clearly different for capacitors and MOS transistors.

### *B. Time-Dependent Dielectric Breakdown*

Oxides quality is often measured by comparing intrinsic breakdown, measured over short time periods by applying a voltage ramp. Recent studies of time-dependent dielectric breakdown (TDDB) have shown that the breakdown characteristics of devices with intermediate-to-large area are dominated by the distribution of impurities within the oxide [4], not the intrinsic breakdown strength. This results in a much lower effective dielectric strength than indicated by intrinsic breakdown. Figure 1 shows some results from that study, done on capacitors with an oxide thickness of 110 Å. The results can be fitted to a bimodal Weibull distribution (the parameter F is the cumulative number of errors). Intrinsic and extrinsic regions are shown.[†] For short time periods, or for capacitors with small area, intrinsic breakdown is dominant. For longer time periods, or for capacitors with large area, extrinsic breakdown – related to defects in the oxide – is the dominant contribution.

TDDB involves constant stress at a fixed voltage, and the mechanisms for TDDB are not directly related to gate rupture from heavy ions. However, the TDDB work is important because gate rupture tests are in fact an *admixture* of a moderate-duration TDDB test with the effects of randomly occurring, short-duration pulses from heavy ions. The TDDB work suggests (1) an inherent time dependence, i.e., that heavy-ion results may be different if the tests are done over longer time periods where the extrinsic breakdown features dominate; and (2) the possibility that heavy ion results may also depend on fluence if impurities are involved in the breakdown process, because ions striking within some neighborhood of an oxide defect may produce breakdown at lower fields than oxides that strike more robust regions of the oxide.

As will be shown later, all of the gate rupture studies done to date require fluences such that there are several ion hits -- ~10 to 1000 -- on each oxide region before breakdown occurs. This suggests that the extrinsic defect distribution plays a significant role in the gate rupture process.

## III. EXPERIMENTAL RESULTS

### *A. Test Structures and Devices*

Capacitors with two different oxide thicknesses were used in this study, 45 and 75 Å, fabricated by MIT Lincoln Laboratories. The gate regions were doped polysilicon, with an n-substrate, doped to approximately $10^{15}$ $cm^{-3}$. The underlying substrate resistivity is about the same as that of the capacitors used in Reference 3, considerably lower than the doping level of the channel in MOS transistors. Capacitors were available with four different areas, from $1.2 \times 10^{-3}$ to $1.1 \times 10^{-2}$ $cm^2$.

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[†]The slope of the extrinsic failure distribution of Figure 1 increases with electric field. This shows that defects play an increasing role over a wide range of field strengths, not just in establishing the number of initial failures at low field. The extrinsic region will be the dominant effect in circuit applications, and will cause the failure rate to be much higher than that predicted from intrinsic breakdown. Extrinsic breakdown may be less important for very thin oxides, but it is clearly a major factor for oxide thicknesses on the order of 100 Å.

Experiments were also done on power MOSFETs from International Rectifier. The oxide thickness of those devices was 750 Å. Power MOSFETs with several different voltage ratings – 100 to 400 volts -- were used; the doping levels of the underlying regions varied from $4 \times 10^{14}$ to $3 \times 10^{15}$ $cm^{-3}$. Including the power MOSFETs in the study allowed breakdown in thick oxides to be compared to breakdown in the much thinner oxides that are representative of integrated circuits. It also allowed the effects of the underlying doping level on breakdown to be determined, at least for thick oxides, as well as providing a connection to gate rupture effects in power MOSFETs, which have been more thoroughly investigated [5]. The power MOSFETs were treated like the capacitors during the tests, applying voltage only to the gate during testing (the source and drain were grounded).

### *B. Experimental Procedure*

Breakdown experiments were done by applying a constant bias to the capacitor, continually monitoring the capacitor voltage during the irradiation. Tests were done at the Brookhaven National Laboratory Van de Graaff. Initial experiments were done using a fluence such that about 2000 ions would strike the capacitor before each test sequence was concluded, adjusting the beam flux and run times so that approximately the same number of ions struck each capacitor during each test run. If no breakdown occurred during that time, then the voltage was increased, and the experiment was repeated at a higher LET. All irradiations were done using ions at normal incidence.

Later tests were done using much higher fluences, increasing the number of ions that struck each capacitor to about 80,000 per test run in order to compare breakdown effects at high and low fluences. These runs were typically completed in 10 to 15 minutes, approximately five times longer than the runs at low fluences.

Capacitors were irradiated in groups of four devices. Voltage on the capacitors was measured with a digital voltmeter, buffered by an operational amplifier. Measurements were made continually during irradiation, providing approximately 0.1 second resolution of the time at which failure occurred. The beam current was monitored to make sure that it remained stable during each run. The power MOSFETs were irradiated individually using an HP4142 measurement system with higher voltage range than that provided by the buffers used in the capacitor experiments.

### *C. Initial Results at Intermediate Fluences*

The results of the tests with heavy ions are shown in Figure 2 for test structures with the two oxide thicknesses. The ordinate shows the critical field (MV/cm), which was corrected for built-in potential. Our results showed that the field strength required to initiate breakdown was higher for the thinner capacitors, in general agreement with the trend of results in Reference 3. However, comparing devices with similar oxide thickness, the electric field strength was somewhat lower for the capacitors in our study than for those in the earlier study. Table 2 below compares the results at an LET of 60 MeV-cm$^2$/mg for our work and the results from the Sandia group [3]. It is possible that the lower critical fields in our study could be entirely due to differences in processing. However, Sexton et al. also observed that the voltage for breakdown in a 256-kB (commercial) SRAM with a 133 Å oxide was somewhat lower than the critical voltage for their 120 Å capacitor structures, comparable to the relative differences in field strength observed between our capacitors and the Sandia capacitors. Much smaller differences between the capacitor and circuit results occurred for a 16-kB SRAM test structure (with smaller total oxide area compared to the 256k SRAM) in their work. This raises the possibility that differences in the test approach and capacitor areas may be a factor in the differences between the various tests. As shown in the table, the number of ions striking each capacitor during each test cycle was approximately an order of magnitude larger for our tests than in the work of Reference 3.

Table 2. Comparison of Oxide Gate Rupture Results for Capacitors

| Oxide Thickness (Å) | Critical Field @ LET = 60 (MV/cm) | Estimated Number of Ions Striking Capacitor | Data Source |
|---|---|---|---|
| 45 | 7.2 | 2000 | Current work |
| 60 | 7.8 | not specified | Reference 3 |
| 65 | 8.2 | 130 | Reference 3 |
| 75 | 5.7 | 2000 | Current work |
| 120 | 6.6 | 130 | Reference 3 |
| 180 | 5.9 | 130 | Reference 3 |

The 45 Å oxide in our study is significantly thinner than the oxides studied previously by Sexton, et al. Breakdown in the 45 Å oxides exhibited a much different signature – soft breakdown – compared to the 75 Å capacitors. Figure 3 shows two examples, taken simultaneously during the same run; both devices were located on the same test chip. One device exhibited an

abrupt change in voltage, but it did not behave like a thick oxide in that the current was limited to about 120 μA. Increasing the applied voltage after breakdown occurred caused only a small incremental change in current; thus, the breakdown was essentially current limited at 120 μA. This is similar to soft breakdown characteristics reported in reliability studies for thin oxides [6,7]. The 75 Å devices were tested with the same hardware, and generally exhibited current increases of several mA (limited by the compliance of the measurement circuit) that increased to larger currents when the voltage across the capacitor was raised after breakdown occurred. Thus, the breakdown signature was quite different for the two different oxides, but consistent with reliability work on oxides with similar thicknesses.

Much different behavior occurred for some of the 45 Å devices. The second curve in Figure 3 shows a very soft breakdown characteristic, limited to about 30 μA. Some noise-like instability occurs after breakdown. As the irradiation continued, a second breakdown event occurred in this same structure with an incremental step of only 10 μA. Such multiple events were frequently observed for the 45 Å capacitors. This type of soft breakdown has also been reported in TDDB studies of oxide breakdown, and generally occurs only for oxides with thicknesses below 50 Å [6-8]. It severely complicates the interpretation of gate rupture experiments in thin oxides. The currents are low, and the nature of the breakdown is completely different from that of thicker oxides. Although the currents are low from the standpoint of measuring them with conventional instrumentation, they are very large currents in the context of the drive current capability of small-area MSOFETs, and would cause failures in most circuits.

*D. Fluence Dependence*

The number of ions required for gate rupture in earlier work [1,2] has been determined, and is shown in Figure 4 along with the new results in this study at intermediate fluences. An average of several hundred to several thousand average "hits" on the total insulator area was required to initiate insulator rupture at moderate field strengths. Even when the electric field was increased many hits were still required for breakdown to occur. It is apparent from these results that the field strength at which breakdown occurs during an experiment will depend on the number of ions that impinge on the insulator area during the run.

Unless experiments with capacitors at moderate fields use a sufficient number of ions, breakdown will not occur, and the critical field will be overestimated. The circuit results imply that differences of about 20% can occur between experiments with low numbers of ions and experiments with high numbers of ions, assuming comparable voltage dependence for the heavy-ion breakdown process.

The fact that breakdown always required multiple "hits" can be interpreted several ways. It is possible that breakdown may be the result of a gradual "weakening" of the oxide by a succession of ions strikes, or simply that some localized regions within the oxide are more sensitive to the breakdown process. This will be discussed further in the next section.

Additional experiments were done using much higher fluences in order to see how the critical voltage would be affected by fluence. Figure 5 shows how the voltage for breakdown compared for 75 Å capacitors at an LET of 37 MeV-cm$^2$/mg. The mean voltage for failure decreased by about 7% at higher fluences. The only difference in these experiments was the fluence used for each test sequence.

*E. Influence of Doping Levels*

Spreading resistance measurements were used to determine the doping density of the underlying epitaxial region in the power MOSFETs. The thickness of the gate regions were measured with a scanning electron microscope. All three MOSFET types had identical gate thicknesses, 750 Å. Their doping levels and epitaxial thicknesses are shown in Table 3.

Measurements of the gate-source voltage required for breakdown were done by subjecting each device to a series of irradiations using fluences of approximately 5 x $10^4$ ions/cm$^2$ for each radiation run (this corresponds to an "intermediate fluence" condition). The voltage was increased in one-volt steps,

Table 3. Properties of the Power MOSFETs

| Type | Rated Drain-Source Voltage | Doping Level | Epitaxial Thickness |
|---|---|---|---|
| 2N6782 | 100 V | 3 x $10^{15}$ cm$^{-3}$ | 15 μm |
| 2N6790 | 200 V | 1 x $10^{15}$ cm$^{-3}$ | 26 μm |
| 2N6786 | 400 V | 4 x $10^{14}$ cm$^{-3}$ | 40 μm |

continuing the irradiation sequence until failure occurred. There were significant differences in the voltage at which breakdown voltage occurred for the different device types, as shown in Figure 6. Three devices of each type were irradiated with each ion type, and the breakdown voltage was very consistent for units of the same type. These results imply that the critical voltage condition for breakdown is somewhat lower for higher doping concentrations than for low doping.

This result may not be directly applicable to highly scaled MOSFETs because the depth of the underlying silicon region is so much smaller. However, the thickness of the underlying region for the 100 V devices is only 15 μm, compared to 40 μm for the 400 V device, and one would normally expect that the thinner region would have less impact on the critical voltage for gate rupture, not more impact. The important point is that if the critical field for structures with very light doping densities is higher, then breakdown may occur at lower fields in devices with higher doping densities. This issue needs to be investigated more thoroughly for devices with shallow structures.

## IV. Discussion

### A. Sensitive Dimensions

The fact that the first ion generally does not initiate breakdown implies that the breakdown process is statistical. Although it is possible that multiple events in close proximity are required to produce breakdown, we have compared test results with capacitors that were irradiated using a progressively increasing series of voltage conditions (multiple irradiations) with experiments done on fresh capacitors that were not previously irradiated, with no apparent differences. Thus, it is more likely that the ions have to strike a small critical region of the device *when the applied field is high enough to cause breakdown at those sites* in order for breakdown to occur. This is consistent with the features of extrinsic breakdown in the TDDB studies of Reference 4; the fraction of devices that fail after a fixed time interval increases with higher field strength. Thus, the field strength at which the capacitors break under TDDB depends is not unique, but depends on the capacitor area and time.

Using the mean number of ions required for breakdown, one can determine the effective fractional area for the breakdown process. For experiments with intermediate fluences, the effective area is about 2 x $10^{-5}$ cm$^2$ for the 75 Å capacitors, and $10^{-5}$ cm$^2$ for the 45 Å capacitors. This may be simply be due to the average distance between the effective number of defects that are involved, or it may be related to both the defect density and the localized distance from each defect in which a heavy ion will cause breakdown to occur.

When the same experiments were repeated at high fluence, the effective area for breakdown decreased substantially. This would not occur if breakdown was associated with a finite number of defect sites. However, the critical voltage was also lower. One way to interpret this is that the higher fluence increases the probability of hitting even weaker defect locations, which have lower critical fields, but are present in smaller numbers.

### B. Random Behavior

One important question is whether failures in the capacitors are truly random events, not associated with the edge of the capacitor or its previous radiation history. Although the thermal diagnostic measurements showed that the perimeter was not involved in typical ion-induced breakdown, this does not directly address the statistical question. Semilogarithmic plots of the number of surviving capacitors vs. fluence are shown in Figure 7 for 75 Å at two different LETs. The data are reasonable fit to a straight line, implying that Poisson statistics apply to the breakdown process. Results from the tests at higher fluences were similar (with lower voltages and much higher fluence values).

Another important issue is whether the breakdown occurs in random locations, or is heavily influenced by edge effects where the electric field is somewhat higher. Figure 8 shows a representative example of defect site after irradiation with heavy ions, determined with a liquid crystal technique that can detect very small changes in temperature (the aluminum over the top of the poly did not allow light emission techniques to be used). The sample shown in the figure was irradiated with approximately 1000 ions before breakdown occurred (intermediate fluence). A small current was allowed to flow in the capacitor during this diagnostic measurement. The defect is well removed from the edge, and appears to be associated with a relatively small thermally heated region (about 2-5 μm) based on a CCD detector with an optical microscope.

The similarity of results with fresh capacitors and those with previous radiation history, the diagnostic measurements and the Poisson-like failure statistics all support the conclusion that breakdown is caused by the passage of a single ion through the capacitor structure. The number of ions required and the dependence on fluence suggests that the ion must strike close to small regions within the capacitor that are more sensitive to breakdown; the sensitive area depends on the applied field.

### *C. Breakdown in Very Thin Oxides*

Another important topic is the breakdown signature of the capacitors. None of the breakdown events in the capacitors were catastrophic. Breakdown produced a resistive path, on the order of 10 to 200 kohms, in the capacitor. Current steps associated with the breakdown were in the range of 80 to 400 μA for the 75 Å capacitors, and 10 to 100 μA for the 45 Å capacitors. In cases of low current breakdown, partially recovery sometimes occurred, and it was possible to observe more than one breakdown event during a heavy ion test. The breakdown characteristics are very important. Radiation tests must be capable of detecting currents in the μA region, as well as distinguishing between hard and soft breakdown.

The soft breakdown characteristics of the 45 Å capacitors are very similar to the breakdown characteristics reported in the reliability literature for TDDB [4-6]. Those results show that soft breakdown is the dominant mechanism for very thin oxides, and it is likely that heavy ions will produce similar characteristics in very thin oxides. Such breakdown events may be difficult to measure in radiation experiments. Oxides as thin as 15 Å have been proposed, where direct tunneling allows significant current flow in the gate [9].

### *D. Effects on Scaled Devices*

The issue of how the gate rupture problem is related to device scaling is a very complex problem. Very high fields – 6 MV/cm or more – have been proposed for future devices [10,11], and the significance of gate rupture in devices will likely depend on how far the electric field strengths are pushed in future device technologies. Sexton, et al. [3] noted that oxide defects will have to be reduced in order to make useable devices at high fields, which may also affect gate rupture susceptibility. However, very few oxides have been subjected to gate rupture experiments, and most of the conclusions about scaling are based on experiments with capacitors. As noted earlier, although capacitors provide insight into some aspects of the phenomena, they cannot necessarily be extended directly to circuits because of the difference in geometry and doping levels.

Results from various radiation tests of gate rupture sensitivity are compared in Figure 9. The capacitor data of Sexton, et al. [3] appear to lie on a straight line. Their tests of a commercial SRAM departed somewhat from the capacitor results, which could be caused by differences in area or by the fact that the SRAM is manufactured with a different process. The results for our capacitors show significantly lower critical voltages than for the Sandia capacitors, and the difference appears to be consistent with the decreased critical voltage observed for the SRAM in the Sandia work. The older 4-Mb DRAM results show even lower critical fields; that may be related to the complex processing required for DRAM capacitors[12] or to differences in the oxide quality.

The results in Figure 9 show that there are substantial variations in the critical voltage for gate rupture for various devices. Part of the difference may be due to different test condition and fluence levels. Although oxides from some processes may have sufficiently high critical fields to be immune to gate rupture, the fields of the more sensitive oxides are in the range of 5-6 MV/cm for ions with high LET. Thus, it is not possible to simply dismiss gate rupture for thin oxides on the basis of scaling alone. More work is needed to understand the mechanisms and the relationship of gate rupture sensitivity to processing and device design. This is particularly important because of the trend towards adapting commercial devices for space, with no control and limited knowledge of device processing and design.

Fortunately, the critical fields appear to be high enough for most devices so that only ions with high LET – well beyond the "iron threshold" where there are very few particles in space – can cause gate rupture. However, it may still be important for systems with large numbers of VLSI devices, which is the trend for many modern space systems.

## V. CONCLUSIONS

The results in this paper show that gate-rupture in scaled devices is a complex problem that is not fully understood. Processing details and oxide defects appear to play a role in the process, and the differences in experimental observations may be due solely to processing differences. However, all of the experiments done to date have shown that many ions must pass through the oxide region before breakdown occurs. When gate rupture occurs, it appears to be associated with a single ion, but not all of the ions are effective in producing rupture.

The critical field is not uniquely defined, but depends on the fluence used during "steps" in the experimental characterization of gate rupture. If the fluence is too low, then the critical field may be overestimated by as much as 15%. This is a potential source of ambiguity and confusion in comparing different test results.

For some processes, the critical field appears to be low enough for gate rupture to occur within the range of anticipated power supply voltages for scaled devices. Even though thin oxides appear to have higher critical fields, the electric field is also projected to increase for scaled devices. The ultimate importance of this effect may depend on how high the internal oxide fields eventually become in practical devices.

Soft breakdown characteristics were observed after gate rupture in 45 Å capacitors, but not in 75 Å capacitors. Soft breakdown produces small changes in current that are difficult to characterize, but are large enough to cause circuit failure if they occur internally in small-area devices. Although the mechanism is somewhat different than for thicker oxides, the critical voltage for soft breakdown was consistent with projections from breakdown in thicker oxides.

Gate rupture in thin oxides is an interesting topic, but it has been studied for relatively few devices and processes. More work needs to be done to increase the level of understanding as well as how it will affect highly scaled commercial devices in space.

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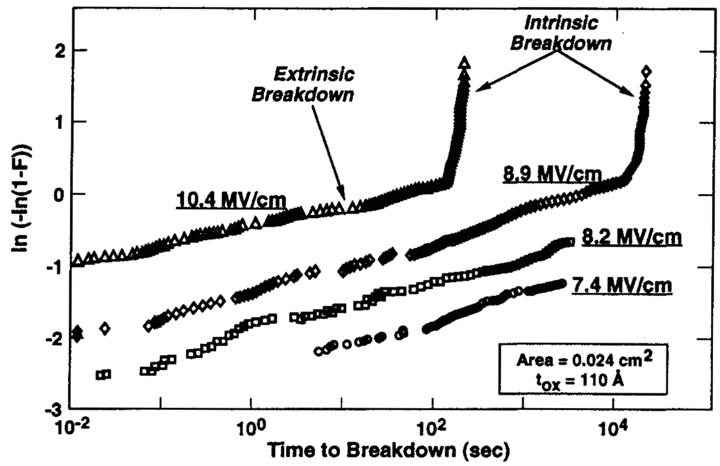


Figure 1. Field Dependence of Intrinsic and Extrinsic Time-Dependent Breakdown (after Ref. 4)

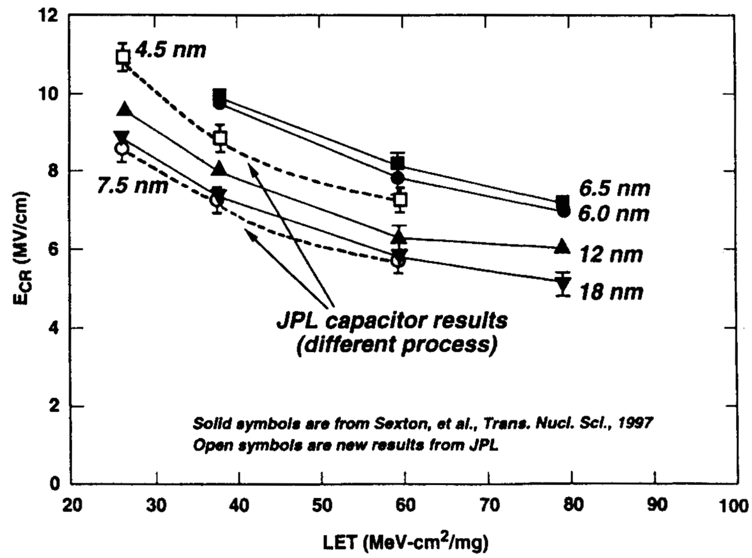


Figure 2. Dependence of Critical Field on Gate Rupture

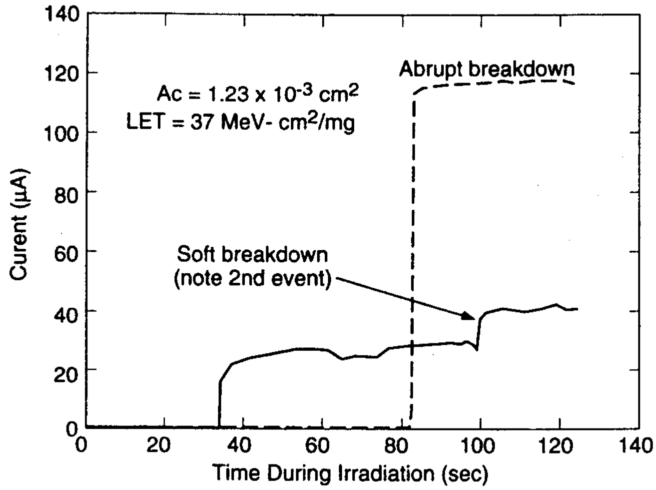


Figure 3. Soft Breakdown Characteristics Observed for 45 Å Capacitors (both capacitors were on the same chip, and irradiated simulataneously).

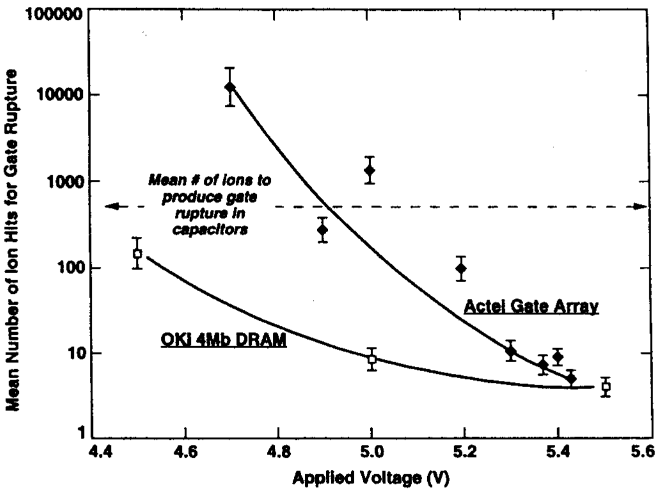


Figure 4. Mean Number of Ions Striking the Active Insulator Area (derived from statistics of circuit results from the original data of References 1 and 2).

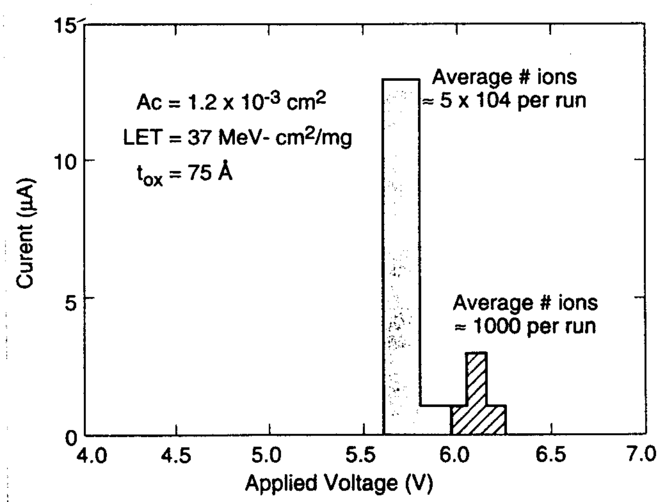


Figure.5. Mean Breakdown Voltage for 75 Å Devices with Two Different Fluence Conditions During Successive Runs.

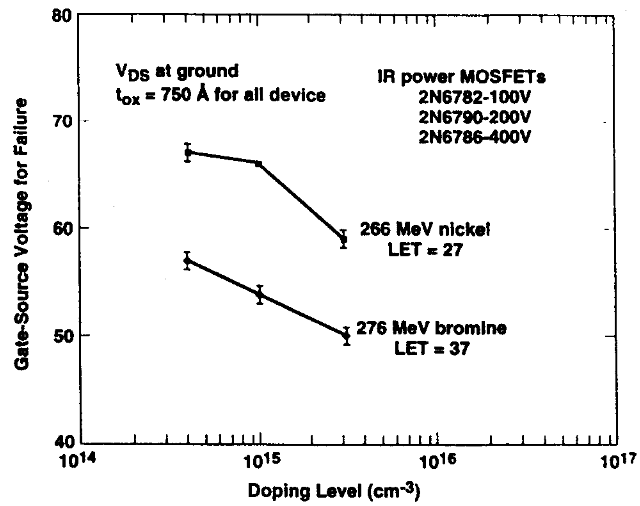


Figure 6. Critical Voltage for Gate-Source Breakdown for the Three Different Power MOSFET Technologies. All Three Have Identical Oxides (750 Å).

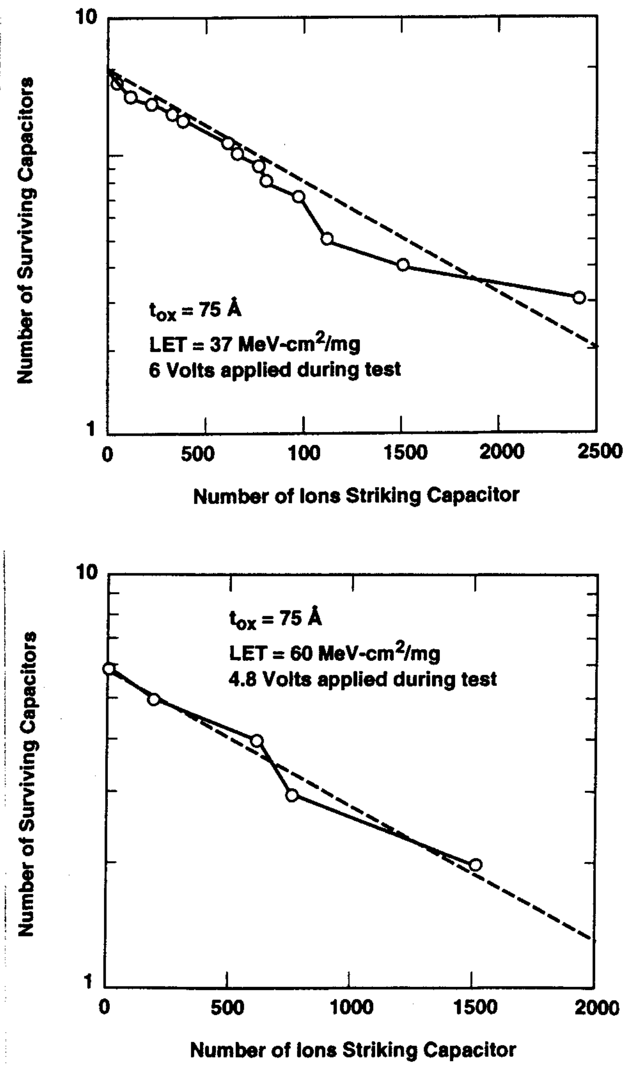


Figure 7. Semilog Plot of Number of Surviving Capacitors vs. Failure Fluence at Two Different LETs. (The data are consistent with Poisson statistics for breakdown).

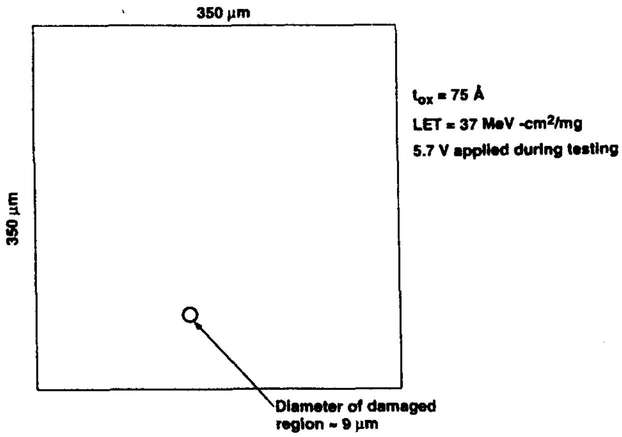


Figure 8. Representative Defect Location after Gate Rupture, Determined with Liquid Crystal Diagnostics. (The actual defect size is probably much smaller than indicated by this technique, which senses small differences in temperature).

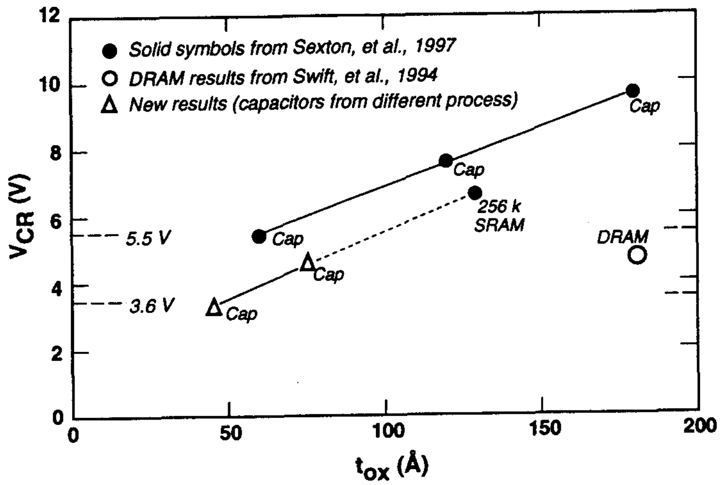


Figure 9. Comparison of Critical Voltages for Various Technologies which Exhibit Gate Rupture.